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Post-combustion carbon dioxide capture using membrane processes: A sensitivity analysis

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Energy saving is the main challenge for post-combustion CO_2 capture technology In this strategy, the target of 90% capture ratio and 90% CO_2 purity are the main constraints to be satisfied.

Membrane process has attracting growing interest for CO_2 capture applications. This work focus on the potential of membrane processes for CO_2 capture for a wide range of process parameters in order to identify the right place and role of membrane processes in CCS technology. A broad range of CO_2 inlet concentration (5%-70%) corresponding to various emission sources has been investigated. Figure 1 shows a diagram of a single-stage membrane separation with feed compression configuration.

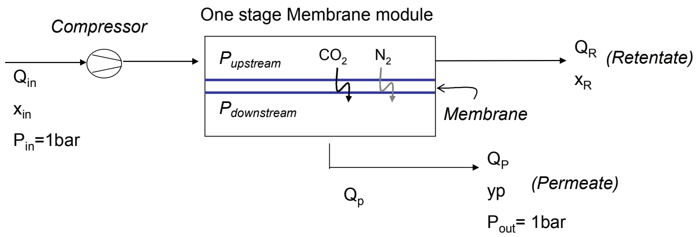

Figure 1: Diagram of a single-stage membrane unit for the post-combustion CO_2 capture - Feed compression configuration

In order to explore the influence of membrane material selectivity CO_2 over N_2 (α) on the process performances, three selectivity values are simulated for that purpose : α=50 corresponding to commercially available membranes and α=100 and 200 corresponding to prospective membranes [1-5]. A large range of process performances in term of CO_2 purity and recovery ratio are investigated and the corresponding energy requirement is compared to the reference technology: MEA absorption. Furthermore, tow compression strategies: feed compression with energy recovery system on the retentate (high pressure side) and vacuum pumping are investigated. Their performances in term of energy requirement and membrane surface area are evaluated and compared.

The modelling of CO_2 capture by gas separation membrane is based on a well known cross-plug flow model. The performances of the separation can be simulated based on numerical resolution of the characteristic mass balance equation. Numerical details can be found elsewhere [6,7].

Figure 2 shows an example of simulation results for a single stage membrane module. The CO_2 recovery ratio is fixed to 0.9 (R=0.9). In this figure the process energy requirement are plotted as a function of the CO_2 permeate purity for different inlet CO_2 content. The membrane selectivity is set at a value of 100. One can remark that the process performance show a strong sensitivity toward CO_2 inlet concentrations.

It can be observed that a permeate CO_2 purity of 90% could obviously be attained in a one stage membrane providing that concentrated CO_2 flue gas (x_{in}>0.2) is to be treated. For diluted CO_2 flue gas, multistage membrane process is needed in other to attain the desired CO_2 purity [8,11]

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Moreover, one can remark that the energy requirement decreases significantly by increasing the inlet CO_2 mole fraction. Thus, there is a substantial benefit derived from strategically increasing the feed gas CO_2 concentration by any number of resourceful means, including flue gas recirculation, supplementary firing, and combustion in oxygen enhanced air (OEA) [12,13].

For a given CO_2 inlet content in the flue gas, one can observe that the energy requirement increases drastically when high purity in the permeate is desired. This observation raises the question of whether the membrane stage could play a role of preconcentation step (with moderate intermediate purity (y = 0.3-0.5) combined with a technology such as cryogenic separation that benefits from a higher inlet CO_2 concentration.

For concentrated CO_2 flue gas (x_{in} =0.5-0.7) corresponding to biogas combustion or emission sources in mild oxycombustion processes or sodium carbonate synthesis processes [ref], the membrane process could play a polishing function to attain more that 90% CO_2 purity with very low energy requirement (0.2-0.5 GJ/ton).

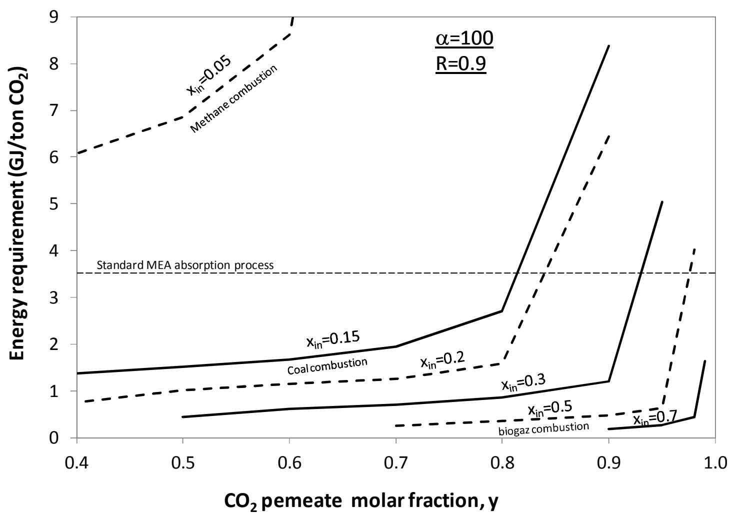

Figure 2: An example of simulation results for a single stage membrane module. Influence of CO_2 inlet fraction on the attainable CO_2 permeate purity (y). A membrane selectivity of 100 and a CO_2 recovery ratio of 0.9 (R) have been imposed for the calculations.

Table 1 summarizes the results of a standalone process for a wide range of inlet CO_2 content (x_{in}=0.15-0.7), for different membrane selectivity.

Table 1: Standalone membrane process: Energy requirement with the target: y=0.9 and R=0.9 – Results for: various CO_2 inlet content for different membrane selectivities.

CO_2 inlet content, x_{in}	Energy requirement, GJ/ton CO_2		
	$\alpha_{CO2/N2}$		
	50	100	200
0.15	-	-	2.90
0.20	-	4.70	1.60
0.30	5.20	1.20	0.95
0.50	0.59	0.48	0.43

0.70	0.23	0.19	0.18

For more concentrated flue gas (x_{in}>0.3), it is shown that there is no significant interest to increase the membrane selectivity up to 100 because much higher membrane surface area will be required with almost the same energy requirement.

Figure 3 gives an overview of the place of the membrane process in post-combustion strategy, for a membrane selectivity of 100, depending on the emission sources, i.e flue gas CO_2 content. The curves corresponding to MEA absorption and cryogenic process are also reported for sake of comparison. In Figure 3, the energy requirement includes CO_2 compression to 110 bar.

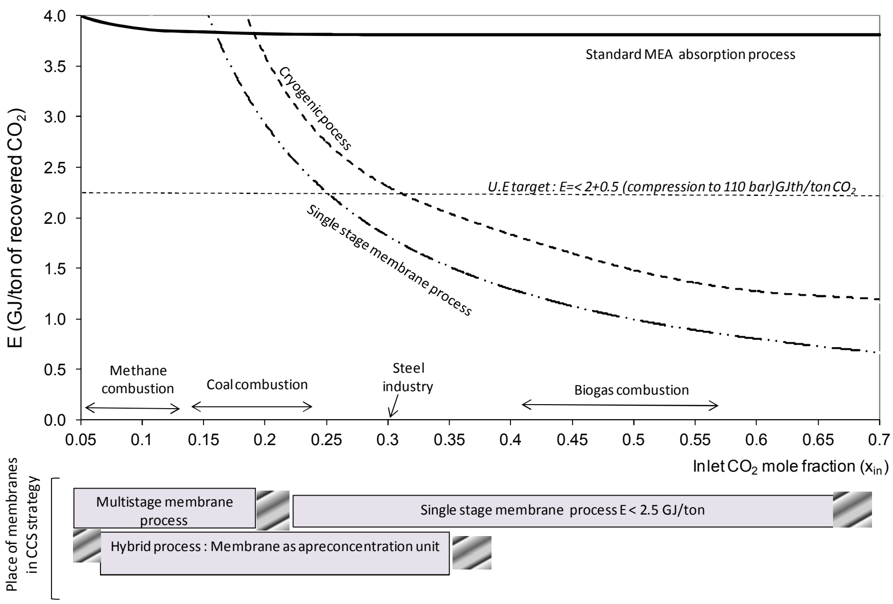

Figure 3: The place of membrane processes in post-combustion strategy depending on the inlet CO_2 mole fraction. Results for membrane selectivity of 100.

Figure 4 shows the membrane surface and the energy required for vacuum pumping and compression with turbo expander strategies as a function of membrane selectivity. The CO_2 pemeance being fixed at 1000 GPU for all membranes. The results are presented for x_{in}=0.3, a CO_2 permeate purity of 0.9 and a recovery ratio of 0.8. From this figure, it can be concluded that:

- Feed compression with ERS strategy leads to a much lower membrane surface area (a factor of ×6 could be attained) while energy requirement remains almost the same with the permeate vacuum energy being slightly lower.
- A trade-off exists between membrane and surface area regarding the CO_2 recovery ratio, the membrane selectivity and the compression strategy. A technico-economic analysis is needed in order to determine the optimum operating parameters and configuration, taking into account both the CAPEX and OPEX of the process.

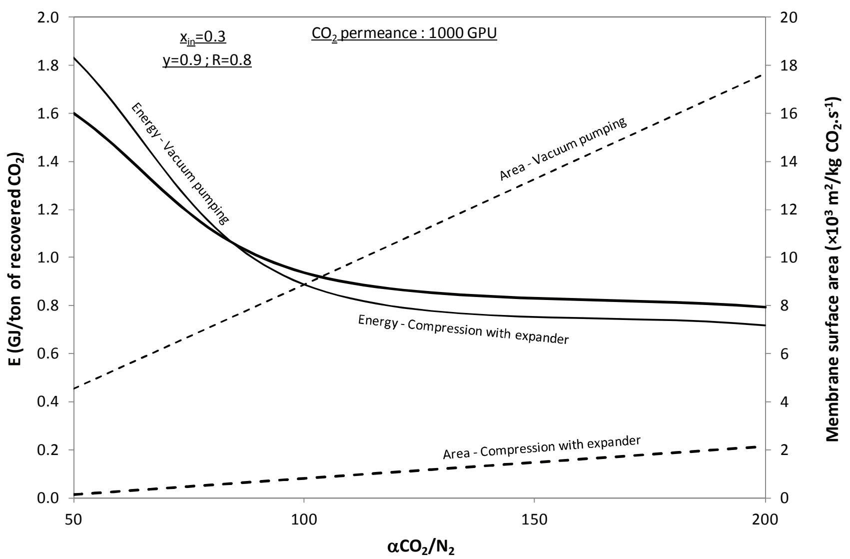

Figure 4: Energy and membrane area as a function of membrane selectivity, permeance =1000 GPU for all membranes. Results are presented for tow compression stategies : (i) compression with expander (ii) vacuum pumping. Results for x_{in}=0.3 and y=R=0.9

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